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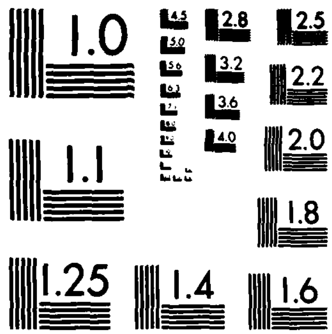

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I. RESEARCH OBJECTIVES

(a) Experiments on Combustion Instability

During the past two years, we have been able to understand, in principle, the mechanism of one predominant mode of combustion instability in dump combustors for ramjet engines. The objectives of ~~the~~ further experiments ~~carried out~~ have been to provide a quantitative, physical basis for elements of this mechanism which will allow application of the results to a wide class of combustor sizes, fuels and mixture ratios, and to more complex acoustic environments. This aim is in support of our original contention, at the outset of the effort, that an understanding of the mechanism rather than the symptoms would provide a basis for quantitative treatment of such problems in general. (to p. 1)

Toward this end, the experiments during the year 1985-86 concentrated on i) the role of the chemical time in the mechanism, as reflected in the mixture ratio and the fuel type, and ii) the importance of non-linear, high amplitude, limit cycles in establishing the steady state. This latter aspect recognizes the fact that it may not be possible to eliminate all unsteadiness from a large combustor, but rather the practical problem reduces to one of minimizing the amplitudes of modes which cannot conveniently be eliminated.

The significant progress in this direction is reviewed in Status of Research, section "a" and "b."

(b) Analytical Studies

The analytical studies which we have undertaken aim to support, extend and generalize the concepts and phenomena which the experiments have shown to be important. There were three specific areas of analytical and computational study which, at the outset of the 1985-86 period, were considered our main objectives. These are i) the generation and motion of the vortex at the dump plane, ii) the vorticity and flow reversal induced in combustion products by an adverse pressure gradient, and iii) the interactions of a weak shock with hot, low density gas regions. Each of these objectives was aimed at the clarification and quantification of phenomena which the experiment indicated to be key issues.

The first of these is discussed in Status of Research, item "a" and the results clarified the phenomenon immensely. The second was completed and is covered, Status of Research, item "b" in detail. The third analytical objective was begun but has progressed to only the initial phase. The preliminary results of this effort were given in the proposal for continuation of the research to the 1986-87 year.

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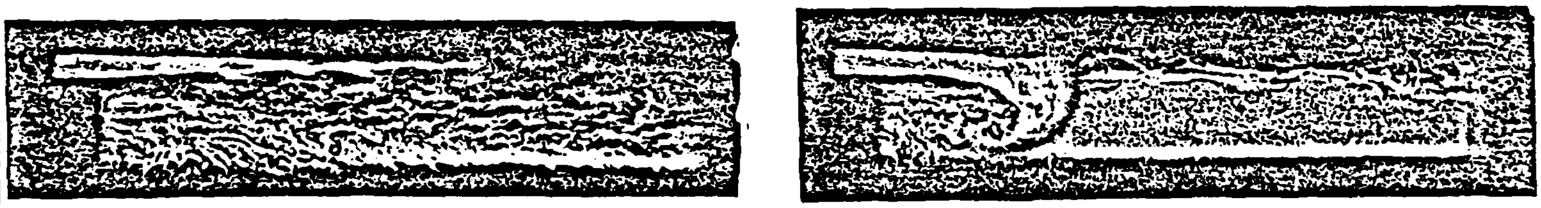
II. STATUS OF RESEARCH

(a) Oscillations of Large Amplitude

An extensive series of experiments concerning the self-excitation of low- frequency oscillations in dump combustors has been pursued during the past two years to determine details of the excitation mechanism in sufficient detail to allow the phenomenon to be scaled over pressure, temperature, geometry, fuel type and mixture. The contrast between flow fields generated by steady combustion and oscillatory combustion is well-illustrated by the shadowgraphs shown in Figure 1.



STABLE FLOW UNSTABLE FLOW

Figure 1.

In these experiments, Smith (1985) and Smith and Zukoski (1985), the motion of the large vortex formed at the flame holder lip just downstream of the dump plane, is tracked by high speed shadowgraph cinematography and the heat release is estimated from time resolved radiation measurements in narrow vertical slits at different distances downstream of the dump plane. The coefficient of correlation between the pressure and radiation intensity fluctuations is shown in Fig. 2.

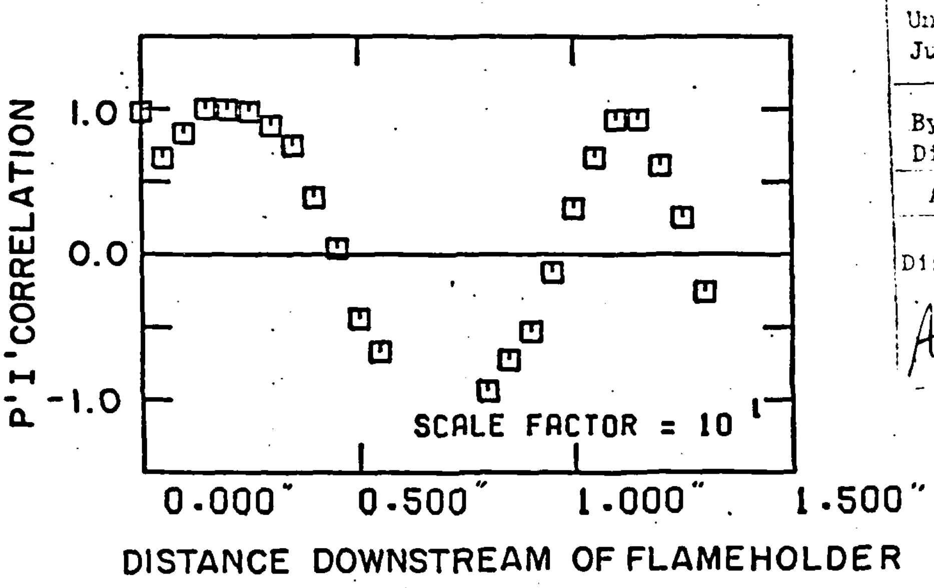


Figure 2.

The quasi-periodic appearance of the correlation has more to do with the downstream transport of the burning vortex than it does with fluctuations in burning rate within the vortex itself.

Analysis of these measurements revealed that the time at which the vortex had moved to the immediate vicinity of the combustor wall coincided with the moment of maximum heat release rate. This suggests, and careful analysis of the data confirm, that the time required for the formation and transport of the vortex to the wall provided the appropriate phase delay in the heat release pulse to reinforce a particular acoustic mode of the system. This implies further that there is a time scale, or a response frequency, built into the vortex formation process which, in turn, selects and locks into a system mode with the appropriate frequency. This picture was clouded, however, when it was observed that the phenomenon, under the same set of operating conditions, could support one of two or three oscillations of very different frequency. Moreover, the oscillatory combustion mode might wander from one mode to the other. As a consequence, the rate of generation and transport of the large vortex became a central issue in unravelling the mechanism controlling these self-sustaining oscillations.

Experiments in which the mean flow rate was varied made it clear that the vortex shedding did not occur at a fixed Strouhal number. But because other conditions are not easily varied with the present limitations of the apparatus, this became one of the cases where the techniques of computational fluid mechanics were part of the experiment. The process of vortex formation and transport is largely an inviscid one and the features in question could be computed utilizing an Euler code. The essence of the phenomenon was modeled as a shock tube with an abrupt enlargement at the dump plane. The portion of the tube ahead of the dump plane and the

projection of this upstream area into the downstream region, contained cold, unburned gas. The gas downstream of the step contained hot combustion products. The event was triggered by sending a weak shock from upstream and tracking the vortex sheet formed at the interface of the burned and unburned gas.

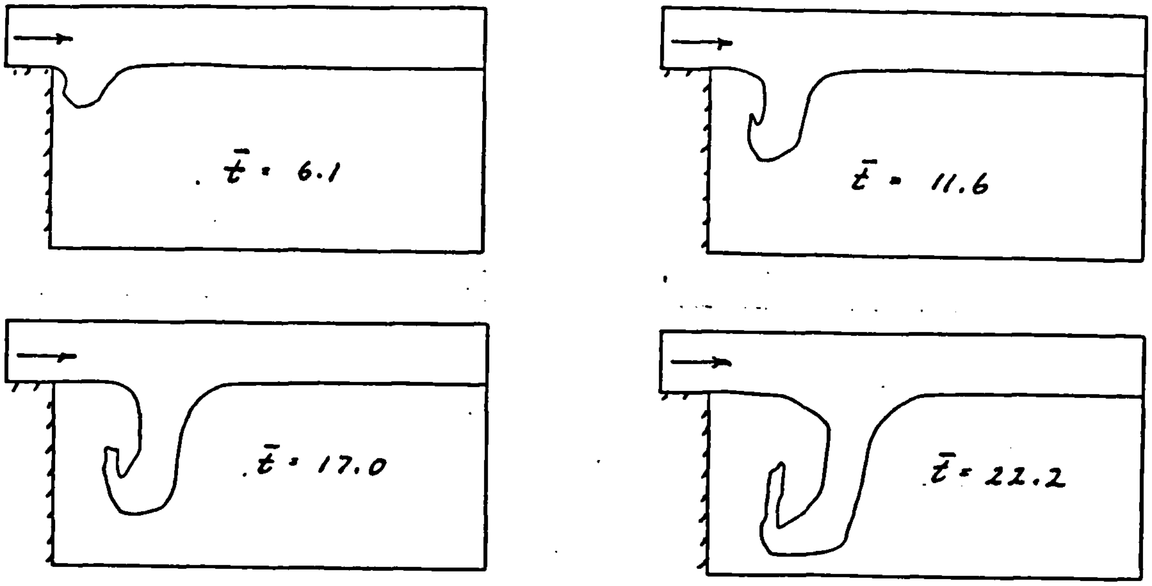


Figure 3.

Figure 3 shows the resulting vortex for several time intervals after the shock has passed the dump plane. Careful examination of the vortex motion showed that, among all the parameters of the problem, only the strength of the initial wave, corresponding to the amplitude of the pressure oscillation in the actual phenomenon, had a sensitive influence.

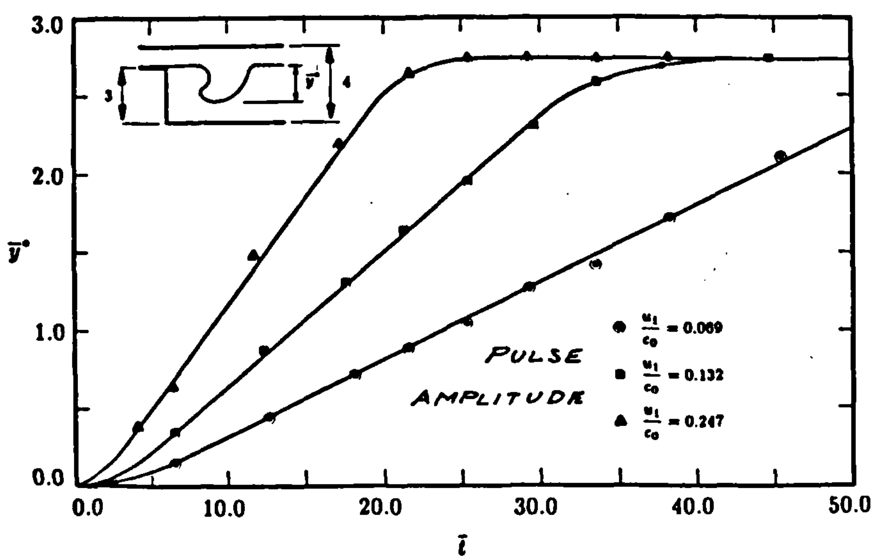
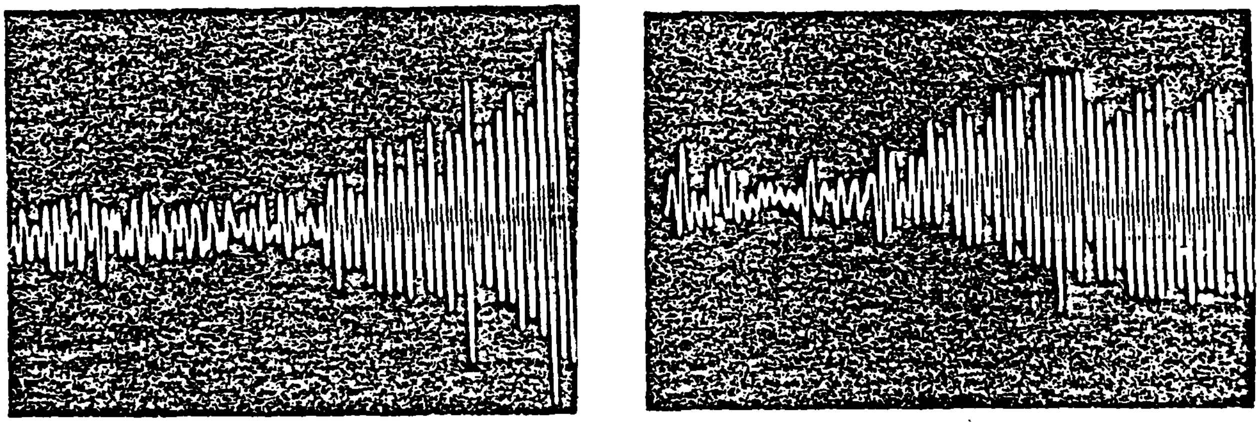


Figure 4.

Figure 4 shows the rate of approach of the vortex toward the wall for three different wave amplitudes. Thus, with other conditions in the problem fixed, higher amplitude pressure oscillations should be able to excite a system mode of higher frequency than an oscillation of lower pressure amplitude.

Now all of the self-excited oscillations observed in these experiments, and certainly those of interest in ramjet engines, have an amplitude sufficiently large that the steady oscillation must be considered non-linear. Correspondingly, the steady oscillations of large amplitude should be considered a limit cycle of the apparatus and the combustion mechanism. The observations cited in the previous paragraph suggest that the excitation term, with the pressure-sensitive time delay, will replace the usual amplitude-sensitive damping in the description of the limit cycle and it is simple to construct a rational differential equation that follows the experimental trends. Experiments are planned to study the details of combustion in the large vortex and it is expected that a rather complete model of the limit cycle oscillation will result.

The suggestion that this process is limit cycle dominated can be reinforced somewhat by experiments carried out in the transient phase where the oscillation is approaching the limit cycle.



PRESSURE, P'   RADIATION, I'

Figure 5.

Figure 5 shows traces of the pressure and radiation intensity measurements as the oscillation is growing from a mode of low amplitude rough burning to a high amplitude limit cycle. Expansion of the time scale shows clearly the non-harmonic character of the oscillation.

(b) The Effect of Mixture Ratio and Fuel Type on the Mechanism of Self Excitation

Past experiments have suggested that the chemical time delay was a factor in the mechanism of low frequency oscillatory combustion but the degree of its importance in establishing the stability boundaries had not been investigated. In a portion of the program directed specifically toward this feature, these instabilities were investigated by using our small laboratory combustor in which the flame was stabilized behind either a single rearward-facing step or a double step as shown in Figure 6. The fuels used

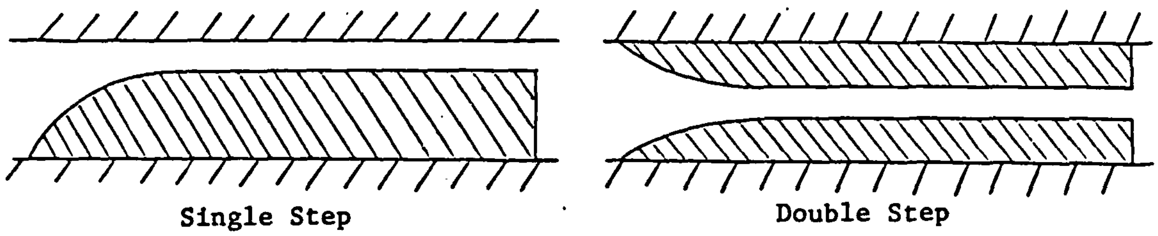


Figure 6.

are methane, a mixture of 15% mass fraction of hydrogen and 85% methane, and a mixture of 30% hydrogen and 70% methane. The fuel and air are premixed and flow from an axisymmetric section to a two-dimensional one as shown in Fig. 7. The combustor has quartz side

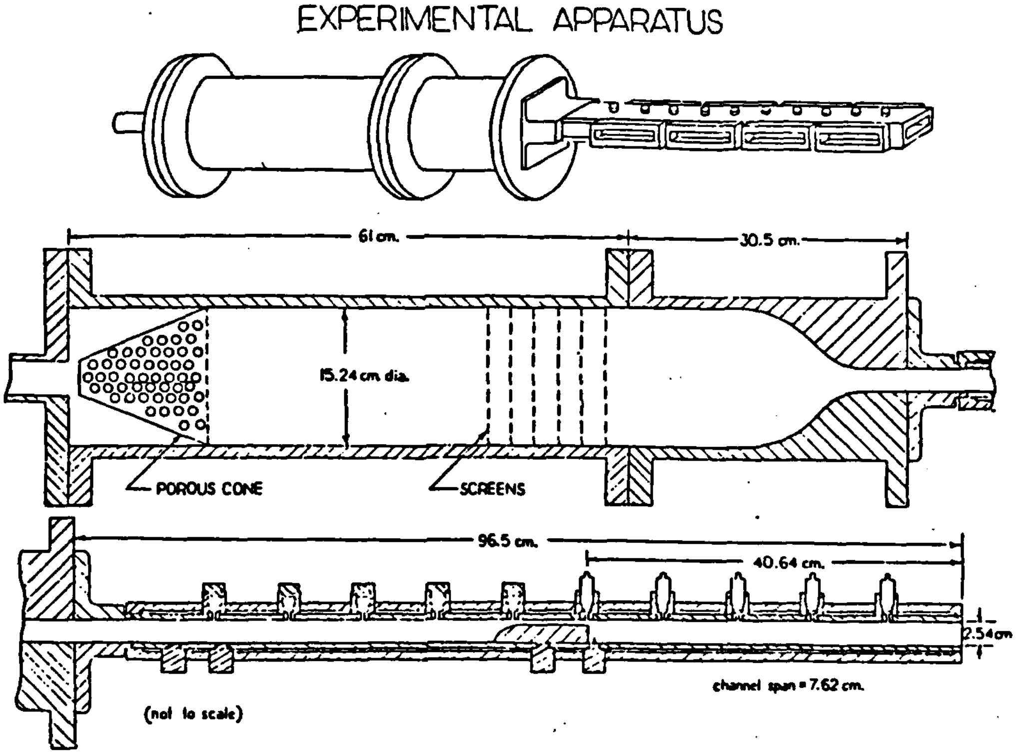


Figure 7.

walls and the top and bottom walls are water cooled.

Spark shadowgraphy is used to observe the flow of the combusting gases. Pressure transducers used to measure the oscillating pressure field are located at various positions within the entire system. Also, the velocity at the flameholder is measured using hot-wire anemometry. The radiation intensity from the flame is measured by a moveable photomultiplier tube which is restricted to view only a small area of the flame zone. We assume here that there is a linear relationship between the fluctuation in light intensity and the fluctuations in volumetric heat release in the observed region. Data was recorded using an SD360 spectrum analyzer.

Changes in step height, Fig. 6, mean flow velocity, and fuel chemistry (i.e. fuel type and equivalence ratio) result in different pressure velocity, and radiation intensity spectra.

Figure 8 shows a typical plot of the dominant vortex shedding frequencies for a fixed geometry and fuel type. The symbol at a particular equivalence ratio and mean flow velocity represents the frequency of the largest peak in the radiation intensity spectra and corresponds to the dominant vortex shedding frequency. Although some variation in the

frequencies does occur, each symbol represents frequencies which are quite close to the corresponding resonant frequency that was predicted by an acoustic model. The cross-hatched region shows the region of stable combustion. The symbols 1, 2, and @ refer to cases where the vortex shedding frequency was 188, 231 and 267 Hertz, respectively.

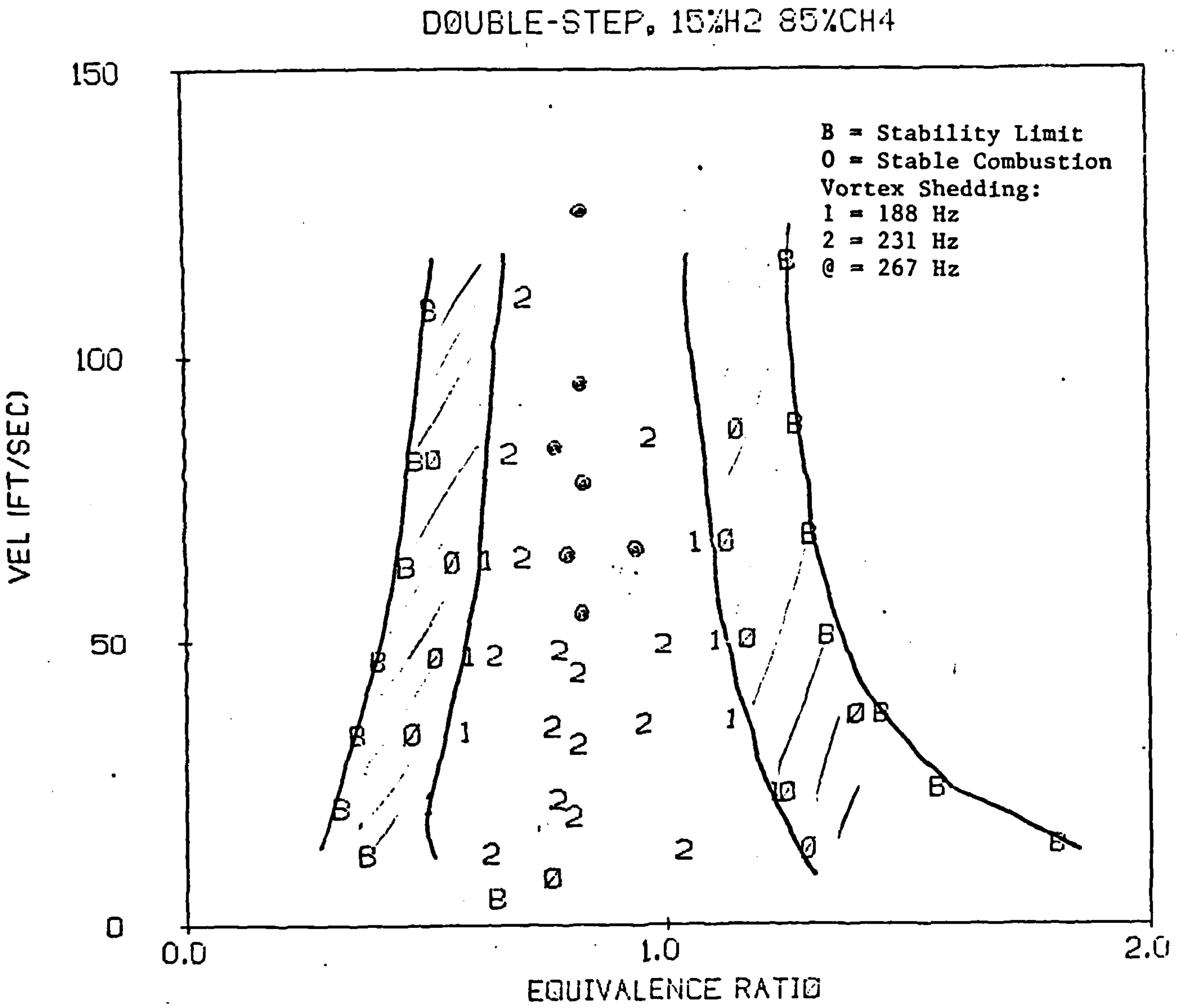


Figure 8. Frequency Dependence Upon Mean Velocity and Equivalence Ratio for a Fuel Composed of Methane Plus 15% H .

From this figure it can be seen that the equivalence ratio has a very strong effect on the unstable mode observed. For a given velocity, the flame can be stabilized with no large vortex shedding, or shedding can occur predominately at one of the three different frequencies depending on the equivalence ratio. The dependence on the mean flow velocity is not as strong; a shift in the dominant shedding frequency can occur solely due to

changes in the mean flow velocity.

(c) The Influence of Strong Pressure Gradients

Perhaps the most unique phenomenon which may occur when combustion regions are subjected to pressure gradients is the rather powerful generation of vorticity in the regions of non-uniform temperature. The mechanism, described by the Helmholtz vorticity equation, results in a rate of vorticity production within an element of fluid proportional to grad(p) x grad(ρ). This means of vorticity production, which is absent for isothermal fields and incompressible fluids, is a major contributing element to mechanisms of self-sustained combustion oscillation in which the pressure gradients are imposed by the pressure waves associated with the unsteady combustion. The nature of the local flow structures that are produced by this mechanism may be examined advantageously in the case of diffusion flames in some regions of which the low density gas is confined to narrow layers. These analytical investigations show also the pronounced, and perhaps unexpected, effect of stoichiometry on the results.

The structure of a diffusion flame embedded in a flow field parallel to the flame has been studied under conditions where this external flow imposes an adverse pressure gradient. It is convenient to think of the physical problem as a flame lying along the flow direction of a divergent channel.

The analysis is accomplished by considering a flow nearly parallel to the horizontal x-axis, the upper half-plane consisting of a fuel, the lower of oxidizer. Further, let the undisturbed gas velocity in each stream be

$$U_1(x) = U_0 (x/\lambda)^{\beta}$$

where U_0 = constant. This represents an idealization of flow of fuel and oxidizer in a two-dimensional channel with the flame lying along the horizontal axis.

The mathematical problem is reduced to a set of ordinary differential equations by (i) employing the Howarth transformation to eliminate the variable density and (ii) introducing a similarity solution somewhat in the manner of the Falkner-Skan treatment of boundary layer flows. Because the low-density gas near the flame responds more readily to the pressure gradient than does the higher density gas, a reverse flow develops in the low density region which severely affects both the structure of the flame and the fuel consumption rate.

In discussing the results of calculations based upon the analysis described, we shall confine ourselves to solutions which correspond to a positive pressure gradient. In Fig. 9, for β = -0.005 and φ = 1, is shown the distribution of all significant quantities including the streamwise velocity, u/U_1, the fuel and oxidizer mass fractions and the normalized temperature distribution $(\theta-1)/(\vartheta_f-1)$. Note that near the flame, where the gas temperature is high and the density correspondingly low, the pressure gradient retards the low-density gas more severely than the free stream gas which causes the diffusion zones to thicken and the diffusion controlled fuel consumption to decrease.

The dimensionless fuel mass consumption rate per unit area at a location x along the horizontal axis is one significant index of the effect of pressure gradient on flame structure. Figure 10 shows that this quantity is a double-valued function of pressure gradient as measured by the index β, and indicates that as $\beta \to 0$ on the lower branch the fuel consumption rate tends toward zero. Note that $|\eta| < 1$ is a region of backflow causing the main streams of fuel and oxidizer to be diverted away from the flame zone. As a consequence, the gas composition in the central region is predominantly combustion products, the composition gradients and the fuel consumption rate are very small.

The phenomenon may be clarified further by examining the streamlines of the flow as a function of x, Fig. 11. This shows the flame lying along the horizontal axis, $\bar{y} = 0$, with streamlines in the central region entering from downstream, moving toward the source, and then being carried out by the two shear layers remote from the flame. It is this dilution of the fuel and oxidizer in the central portion, near the flame, that leads to the low fuel consumption rates on the lower branch of Fig. 10.

In contrast to this first example for $\varphi = 1$, which possesses a natural symmetry, consider methane in air for which $\varphi = 0.058$; the calculated results for $\beta = -0.015$ are shown in Fig. 12. The diffusion flame for this stoichiometry establishes its structure by moving into the oxidizer side, thereby steepening the oxidizer concentration gradient and decreasing the fuel concentration gradient. This relative velocity normal to the flame, shown in Fig. 12, carries the hot combustion products into the fuel side of the flow, causing the temperature distribution to be asymmetric. Because the low density (high temperature) gas lies predominantly on the fuel side of the flame, it is in this region that the adverse pressure gradient is most effective and results in establishing the asymmetric velocity retardation shown. The contrast between $\varphi = 1$ and $\varphi < 1$ is made even clearer by the response of the fuel consumption to pressure gradient, Fig. 13. The behavior of the lower branch is remarkably different in that the decrease below the upper branch is less pronounced than for $\varphi = 1$ and, in particular, that the fuel consumption does not vanish as β returns to zero. This results from a significant feature, which may be seen in Fig. 12, that the reverse flow occurs in a region where the fuel mass fraction is of the order of 0.4 and thus has no strong tendency to reduce the concentration gradient further. The fuel consumption rate is therefore not decreased as markedly as it is in the symmetric patterns corresponding to $\varphi = 1.0$.

This character is further illustrated by considering the case on the lower branch of Fig. 12 where $\beta = -0.001$; the distributions are shown in Fig. 14 and the streamline patterns in Fig. 15. The streamlines show best the changes in character that have taken place. There now exists a broad but asymmetric recirculation within which gas is drawn from downstream in the backflow region and is then swept up and discharged on either side of this region. Reference to the distribution curves, Fig. 14 shows that this entire phenomenon again takes place within the fuel side of the flame structure; the flame tends to lie remote from the recirculation phenomenon.

There is a decisive change in character, shown in Figs. 9 and 14, from reacting flow fields in neutral or negative pressure gradients. Briefly, it is that the two shear layers have become remote from each other, in fact one might say that the flow experienced an "internal separation."

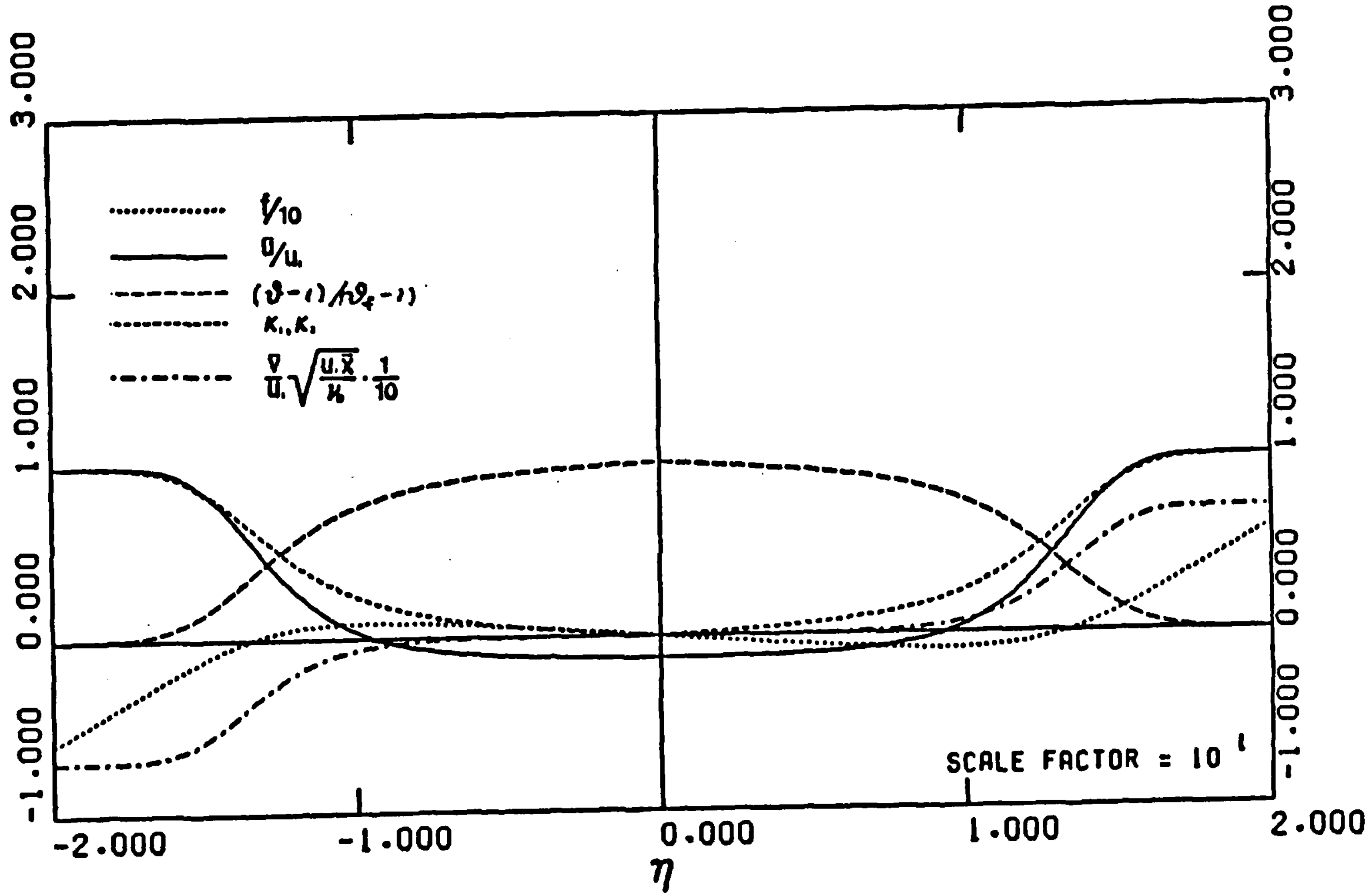


FIGURE 9. Distribution of Properties in Diffusion Flame, φ = 1.0, β = -0.005.

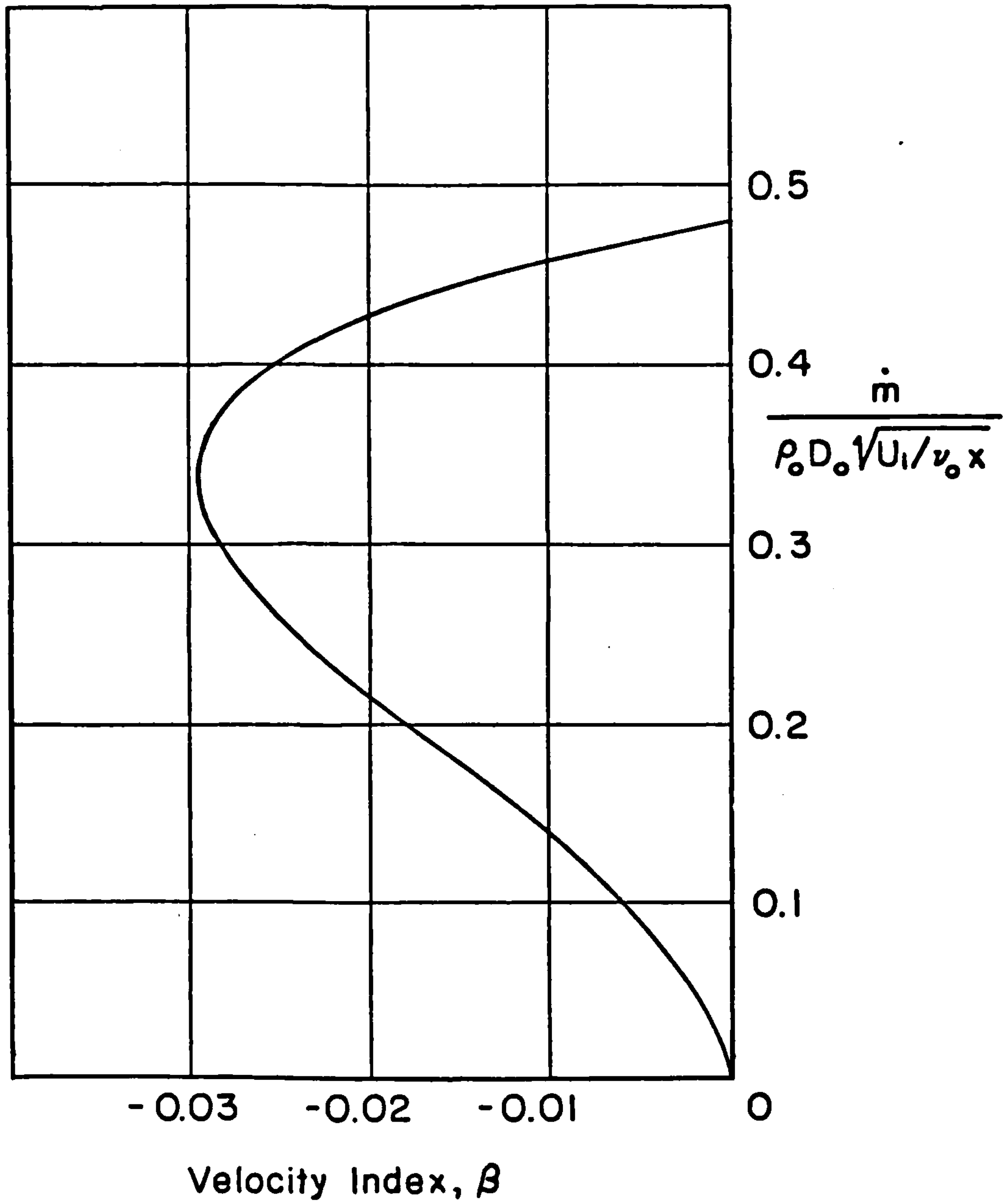


FIGURE 10. Dimensionless Fuel Mass Consumption Rate as Function of Pressure Gradient, φ = 1.0.

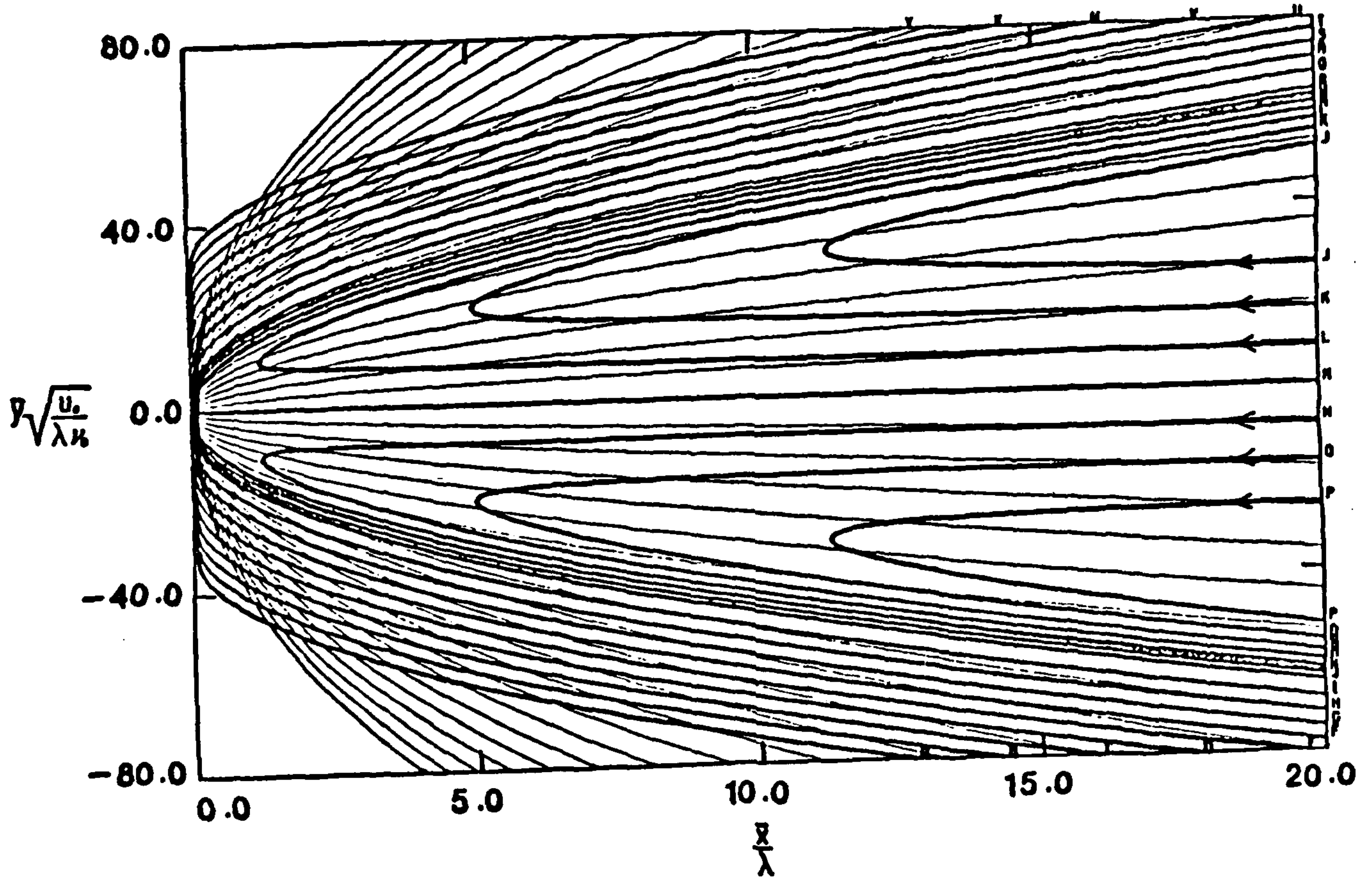


FIGURE 11. Streamline Patterns in Diffusion Flame, $\varphi = 1.0$, $\beta = -0.0005$.

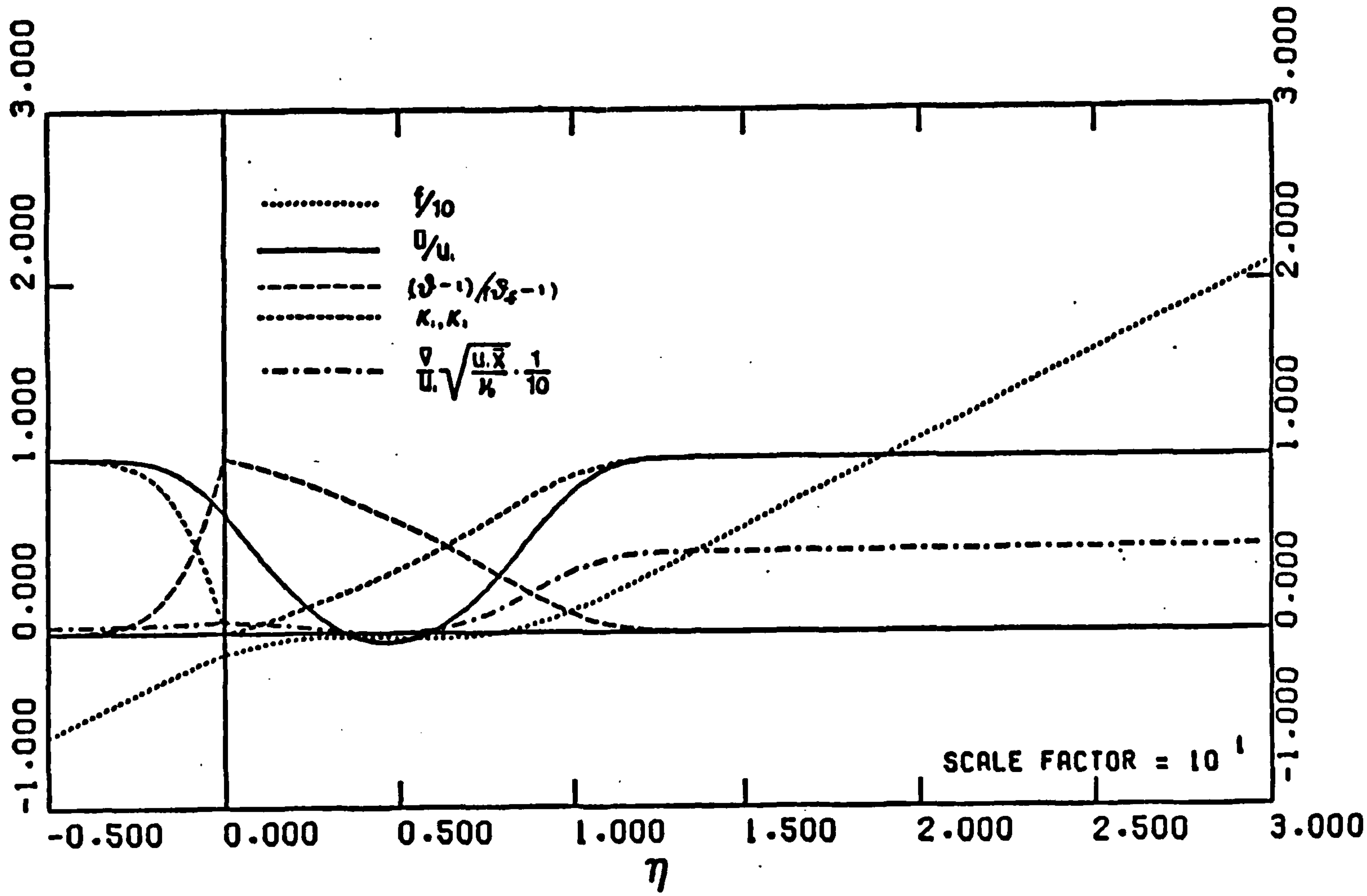


FIGURE 12. Distribution of Properties in Diffusion Flame, φ = 0.058, β = -0.015.

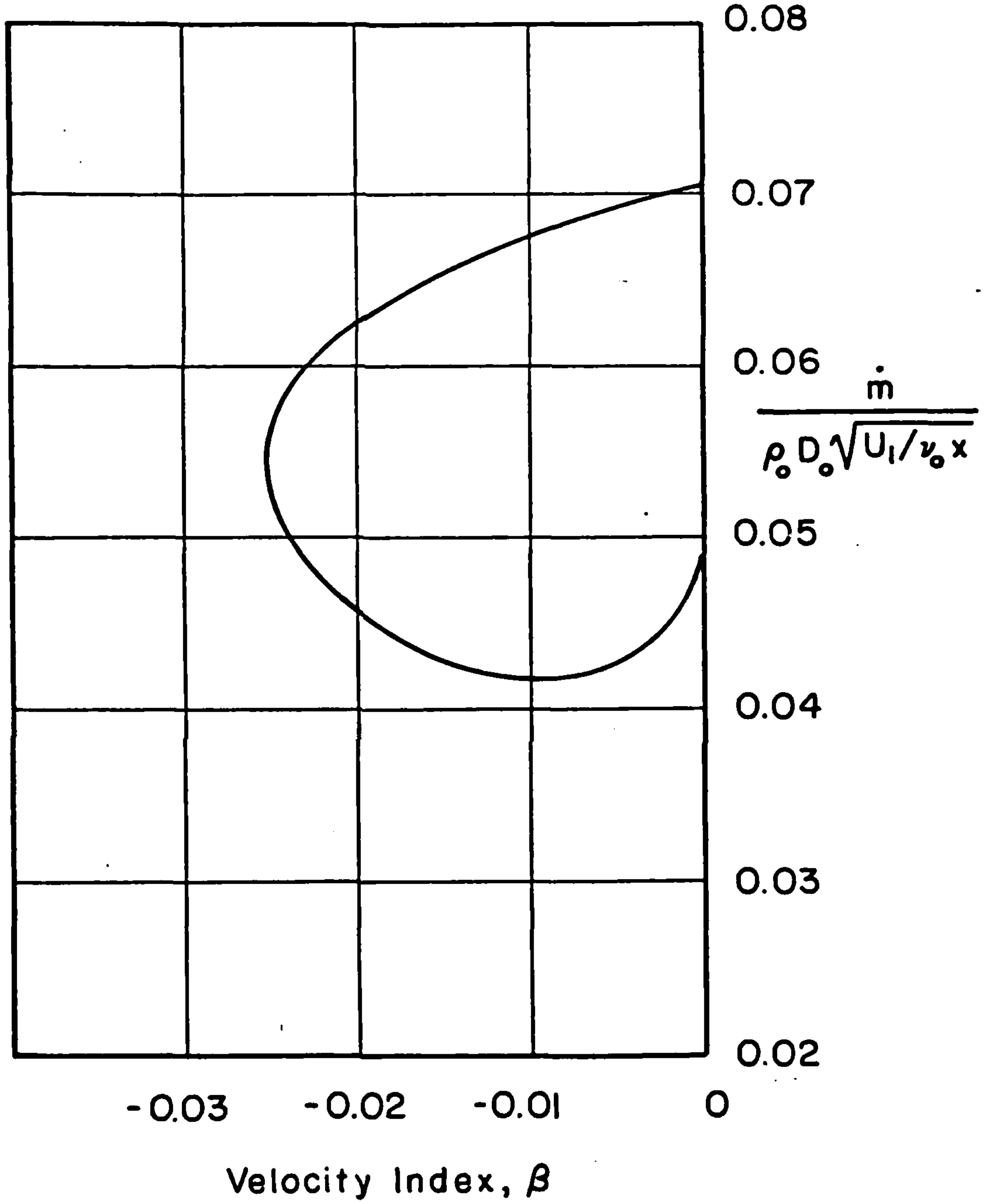


FIGURE 13. Dimensionless Fuel Mass Consumption Rate as Function of Pressure Gradient, φ = 0.058.

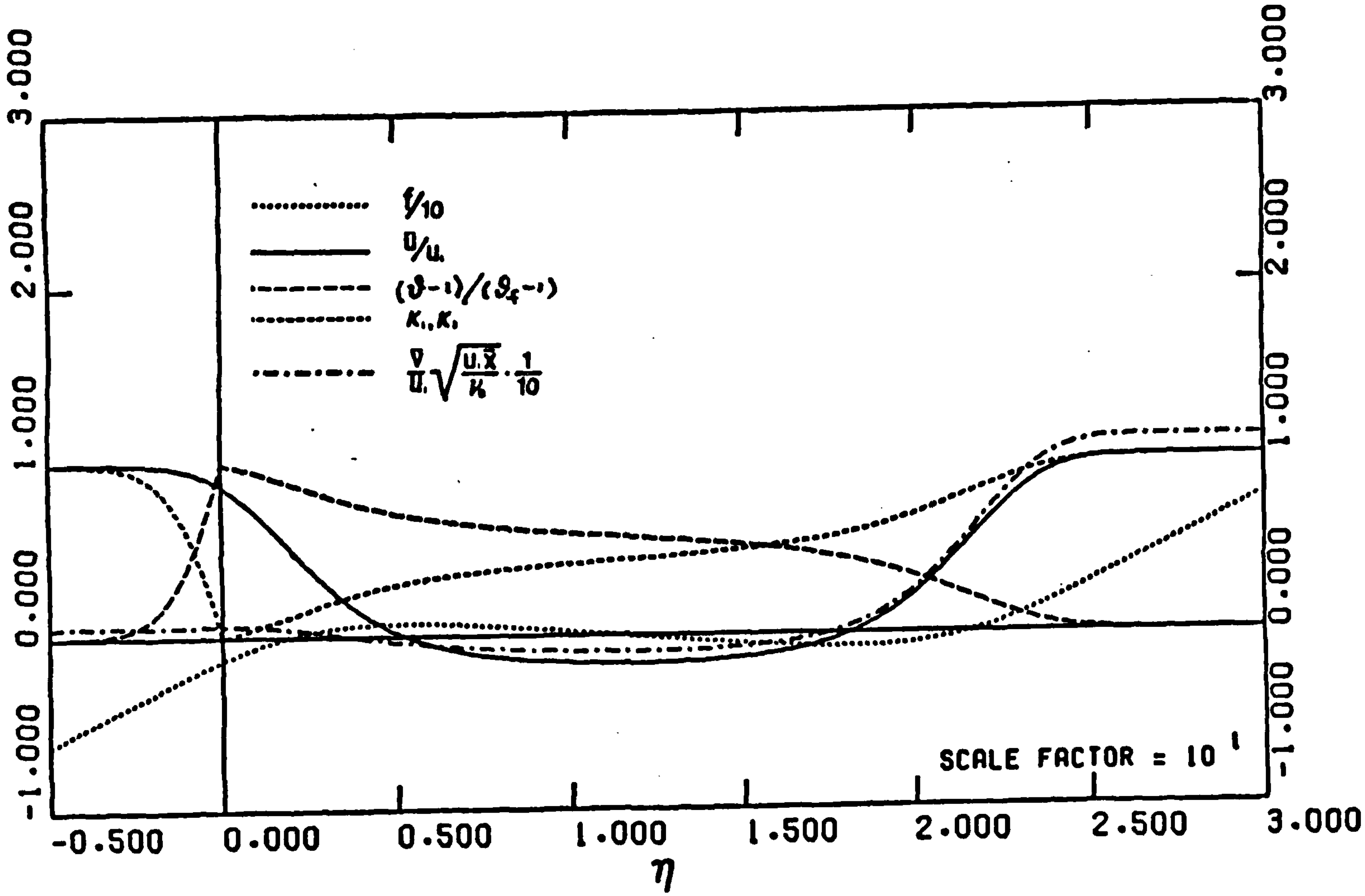


FIGURE 14. Distribution of Properties in Diffusion Flame, $\varphi = 0.058$, $\beta = -0.001$.

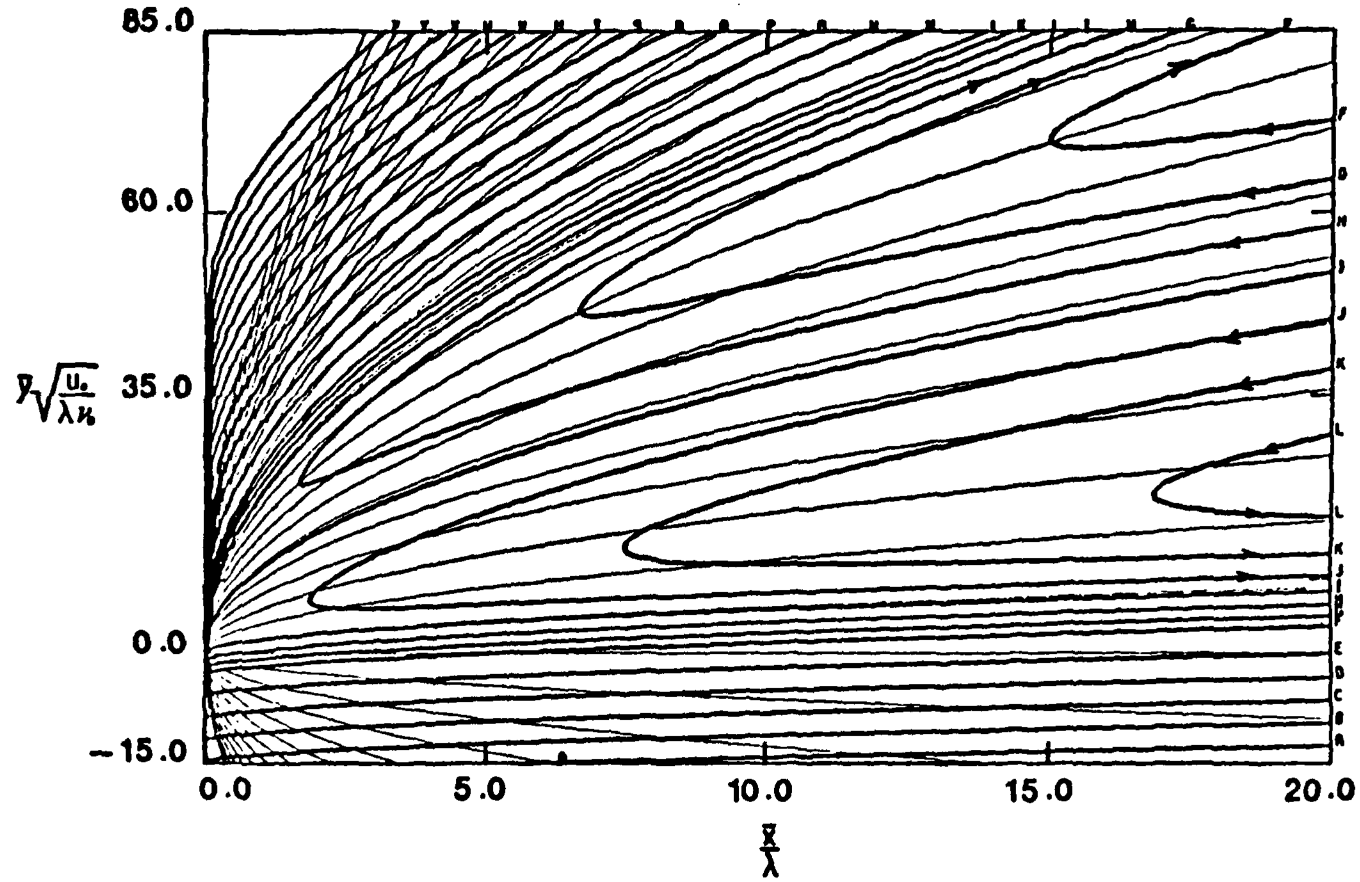


FIGURE 15. Streamline Patterns in Diffusion Flame, ρ = 0.058, β = -0.001.

Nomenclature

D	Coefficient of molecular diffusion
f	Dimensionless stream function
$\dot{m}_f$	Mass consumption rate of fuel per unit flame area
p	Gas pressure
T	Gas temperature
T_o	Reference free-stream temperature
U_o	Reference velocity
U_1	Free-stream velocity
u, v	Local velocity components
$\bar{u}, \bar{v}$	Transformed velocity components
x, y	Cartesian coordinates
$\bar{x}, \bar{y}$	Transformed cartesian coordinates
β	Stream velocity index
K_1, K_2	Mass fractions of fuel, oxidizer
η	Similarity variable, $\bar{y}\{U_1/\nu_o\bar{x}\}^{1/2}$
ϑ	Dimensionless temperature, T/T_o
λ	Reference length scale
μ	Gas viscosity
ν_o	Reference kinematic viscosity
ρ_o	Free-stream gas density
φ	Stoichiometric mixture ratio

III. PUBLICATIONS

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IV. Personnel

Faculty

F. E. C. Culick
F. E. Marble
E. E. Zukoski

Graduate Research Students

G. Hendricks
J. Humphrey
T. Sobota
J. Sterling
T. Zsak

V. Interactions with Industrial and Government Research Groups

Professor Culick has maintained continuing contacts with two groups at the Naval Weapons Center (Dr. K. Schadow and Dr. William Clark). A summary of their collaboration will appear in a paper accepted for publication in the AIAA Journal of Propulsion and Power. Professor Culick also continues exchange of information with groups at Wright Field, the Johns Hopkins Applied Physics Laboratory and the McDonnell-Douglas Research Laboratory.

Professor Marble has a continuing association with NASA Lewis in the field of non-steady combustion and combustion-related turbine cooling problems. In addition he spends some time each year with the Gas Turbine Laboratory of the Massachusetts Institute of Technology on problems of combustion, turbomachinery instability, and combustion related turbine cooling problems. Professor Marble is a consultant to Northrop Aircraft on propulsion and combustion problems.

Professor Zukoski has served as an advisor to the U. S. Air Force, through the Aerospace Corporation, concerning unsteady hydrogen combustion in the exhaust duct of the S.S.M.E. engine at the Vandenburg Satellite Launching Facility. He also makes regular visits to Wright-Patterson Air Force Base concerning mutual interests in ramjet combustion.

END

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